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Effect of trailing edge serration-flow misalignment on airfoil noise emissions

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ABSTRACT

The broadband noise generated by the scattering of turbulent flow at the trailing edge of a NACA 0018 airfoil with trailing edge serrations is investigated, varying both the airfoil angle of attack and serration flap angle. Acoustic emissions from the trailing edge are measured using a microphone array. The noise level is observed to be higher than that of the airfoil without serrations at frequencies beyond a crossover value. The latter is found to scale with a characteristic Strouhal number based upon the boundary layer thickness and the freestream velocity. A satisfactory collapse of the results under varying angles of attack and freestream velocities is observed. The modifications of the hydrodynamic behavior and the noise increase are linked by high-speed observations conducted with particle image velocimetry. An increase in the energy of turbulent fluctuations is also observed at the expected crossover frequency. The dominant cause of the increased noise is thereby identified at the pressure side edge of the serrations at a given flap angle.

1. Introduction

The scattering of surface pressure fluctuations at the airfoil trailing edge, driven by the turbulence in the boundary layer, becomes the most dominant source of airfoil self-noise at low Mach numbers [1]. As a solution to mitigate this source of noise, serrated trailing edges have been proposed as a means to reduce the efficiency by which this scattering occurs. Models that predict the level of noise reduction have been suggested by [2,3], and experimental proof of the noise reduction is provided in [4–7]. The latter have observed reductions of up to 7 dB in wind tunnel measurements, in some contrast with the reduction levels predicted by [2,8], which exceed 10 dB. Predictions by [3] yield noise reduction levels closer to those observed experimentally.

While noise reduction has been demonstrated consistently in wind tunnel measurements, an increase in noise beyond a certain frequency, called the crossover frequency, has also been observed [4,9–12]. This departure is not foreseen in the analytical models proposed by [2,8,3], and has been ascribed to the increased turbulence intensity observed in the regions between serration teeth [5].

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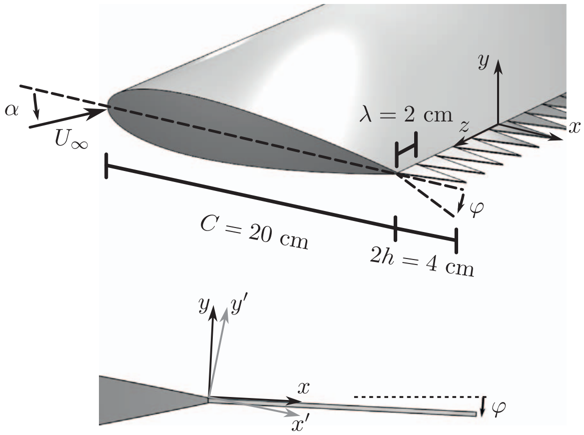

Fig. 1. Airfoil and serration dimensions (top), and convention used for the coordinate system rotation over the airfoil and serration surfaces (bottom).

The increase is particularly evident when the serrated edge is not aligned with the undisturbed wake flow [10] due to a rotation about the z axis (see Fig. 1). This condition occurs when the airfoil is at incidence, and is even more pronounced when the serration has a flap angle [13], although it can happen even at zero values of both if the airfoil has a camber that results in a that results in a downwash at the near-trailing edge wake. The condition in which the serrated trailing edge is not aligned with the undisturbed wake flow of the unserrated airfoil will be referred to as serration-flow misalignment. In the present work, the degree of misalignment is given in terms of the angle of attack of the airfoil and the flap angle of the serrations.

This condition is relevant in the industrial use of trailing edge serrations, such as in wind turbine blades. Situations which lead to a misalignment of the serration with respect to the undisturbed wake flow are common: the large range of angles of attack at which blade sections are operated, departures from the installation or manufacturing tolerances, and the prevalent use of cambered airfoils are a few examples. A certain level of misalignment must therefore be expected, and an investigation into how this causes the undesired increase in noise is essential.

The frequency above which this increase occurs is termed the crossover frequency, f_c , following [10]. It is correlated to the boundary layer thickness δ_{99} (for simplicity contracted to δ) and the inflow velocity, U_∞, through a constant Strouhal number

$$\mathrm{St_c} = \frac{f_c \delta}{U_\infty}. \tag{1}$$

[10] proposed a value of $\mathrm{St_c} \approx 1$, found empirically from measurements of several serration geometries, retrofitted on a NACA 6512-10 airfoil, and run at flow velocities ranging from 20 to 70 m/s. Different angles of attack were also tested during this research, ranging from 0 ° to 15 °, but it is not evident in [10] at which the results of the Strouhal number are discussed. In [14], results are presented for $\alpha = 0$ ° and 5 °. The experimental measurements of $\mathrm{St_c}$ for the different cases collapse around $\mathrm{St_c} = 1$ with an uncertainty of 30%. The variance was attributed to the accuracy of the boundary layer estimation, which was not measured for all flow velocities, but was instead calculated using XFOIL. The authors further suggested that the collapse of $\mathrm{St_c}$ is expected to improve if spanwise variations of the boundary layer, introduced by the irregularity of the serrated edge, were to be considered.

Besides the pioneering work in [15,5], and later [12], no other studies have tried to link the effect of serration misalignment to the important noise increase at high frequencies, despite its critical importance for the effective application of these devices in industrial settings. Moreover, detailed flow field measurements in addition to acoustic measurements are needed to provide insight into the origin of this effect.

Therefore, in order to confirm the observations in [15,5] regarding the Strouhal number, and to further explore the relation between the hydrodynamic flow behavior and the noise increase, the present study employs a combination of acoustic microphone array measurements and flow field data obtained via particle image velocimetry.

A NACA 0018 airfoil, with its original straight trailing edge, and fitted with serrations, is experimentally tested at different freestream velocities. Multiple serration flap angles, φ, and angles of attack, α, are prescribed as sources of serration-flow misalignment. Time-averaged flow information is obtained with stereoscopic particle image velocimetry (PIV, [16]), by which the boundary layer near the edge is studied. Its thickness is measured from the straight-edge airfoil and, with the acoustic measurements of f_c, the crossover Strouhal values are calculated.

Time-resolved PIV is then employed to inspect the flow dynamic behavior and reveal the link between the turbulent flow in the boundary layer and the far field acoustic spectra. In particular, parameters such as the streamwise length scales and most energy-bearing eddies are compared near the edge between the straight-edge and the serrated-edge airfoils. The